Mapping Environmental Injustices: Pitfalls and Potential of Geographic Information Systems in Assessing Environmental Health and Equity

Juliana Maantay

Department of Geology and Geography, Lehman College, City University of New York, Bronx, New York, USA

Geographic Information Systems (GIS) have been used increasingly to map instances of environmental injustice, the disproportionate exposure of certain populations to environmental hazards. Some of the technical and analytic difficulties of mapping environmental injustice are outlined in this article, along with suggestions for using GIS to better assess and predict environmental health and equity. I examine 13 GIS-based environmental equity studies conducted within the past decade and use a study of noxious land use locations in the Bronx, New York, to illustrate and evaluate the differences in two common methods of determining exposure extent and the characteristics of proximate populations. Unresolved issues in mapping environmental equity and health include lack of comprehensive hazards databases; the inadequacy of current exposure indices; the need to develop realistic methodologies for determining the geographic extent of exposure and the characteristics of the affected populations; and the paucity and insufficiency of health assessment data. GIS have great potential to help us understand the spatial relationship between pollution and health. Refinements in exposure indices; the use of dispersion modeling and advanced proximity analysis; the application of neighborhood-scale analysis; and the consideration of other factors such as zoning and planning policies will enable more conclusive findings. The environmental equity studies reviewed in this article found a disproportionate environmental burden based on race and/or income. It is critical now to demonstrate correspondence between environmental burdens and adverse health impacts—to show the disproportionate effects of pollution rather than just the disproportionate distribution of pollution sources. ***Key words*****: environmental hazards, environmental health, environmental justice, exposure analysis, Geographic Information Systems, GIS, risk assessment, spatial analysis.**
Environ Health Perspect **110(suppl 2):161–171 (2002).**
http://ehpnet1.niehs.nih.gov/docs/2002/suppl-2/161-171maantay/abstract.html

Mapping Environmental Injustices

Although the mainstream environmental movement of the 1950s and 1960s alerted the public to the dangers posed by pollution and environmental degradation, these impacts on people's health and the environment were not generally acknowledged (or thought) to be spatially or socially differentiated: everyone was presumed to be affected just about equally. The understanding that environmental problems may impact certain locations and people more than others (and in a predictable pattern based on race and income) is a relatively new concept that gained nationwide attention in the late 1980s.

Environmental injustice can be defined as the disproportionate exposure of communities of color and the poor to pollution, and its concomitant effects on health and environment, as well as the unequal environmental protection and environmental quality provided through laws, regulations, governmental programs, enforcement, and policies (*1–3*).

Within the past decade it has become increasingly prevalent to try to map instances of environmental injustice, usually by geographically plotting facilities or land uses suspected of posing an environmental and human health hazard or risk, and then trying to determine the racial, ethnic, and economic characteristics of the potentially affected populations compared with a reference population. This often results in dramatic maps showing toxic facilities concentrated in areas with high proportions of African Americans, Latinos, or Native Americans (*4–8*). Mapping became a favored method among researchers attempting to determine the existence of environmental injustice. Additionally, the wealth of environmental and demographic data now available on the Internet, as well as the proliferation of websites with interactive mapping applications available, have brought environmental justice mapping within reach of virtually anyone (*9*).

Although such maps can be unusually effective in visually demonstrating the disproportionate spatial distribution of noxious or hazardous facilities, these maps have also come under scrutiny and been criticized for being misleading and inaccurate, and their findings have often been contradicted by other spatial analyses. Mapping a phenomenon such as environmental injustice is not a straightforward exercise, and the difficulties encountered in producing such spatial analyses leave the maps open to a variety of interpretations and second-guessing. Just as no map can be viewed as an objective embodiment of the real world, maps depicting environmental injustice are also social constructions, and therefore subjective and based on assumptions (*10,11*).

A fundamental concern with mapping environmental injustice is that it does not yield definitive findings about differential exposure levels or health outcomes for the population in proximity to the noxious facilities or land uses. This drawback makes these studies less useful in conclusively demonstrating (and measuring) the correspondence between the location of potential environmental burdens, exposures, and health effects. However, it is feasible to develop methods and tools for producing more meaningful spatial analyses. Some of the issues that are contested in mapping environmental injustice, and the technical and analytic difficulties encountered in such mapping projects, are outlined below (*12*), along with some suggestions for using Geographical Information Systems (GIS) to better assess and predict environmental and health conditions.

The Findings of Environmental Justice Spatial Analyses

The groundbreaking environmental justice study, "Toxic Wastes and Race in the United States: A National Report on the Racial and Socio-Economic Characteristics of Communities with Hazardous Waste Sites," was produced in 1987 under the auspices of the United Church of Christ's Commission for Racial Justice (*4*). The report presented maps of the locations of the country's hazardous waste facilities in conjunction with the characteristics of the nearest populations (by ZIP code), using indicators such as race, ethnicity, and income. Compared with the areas that were

This article is part of the monograph *Advancing Environmental Justice through Community-Based Participatory Research.*
Address correspondence to J. Maantay, Dept. of Geology and Geography, 250 Bedford Park Blvd. West, City University of New York, Lehman College, Bronx, NY 10468 USA. Telephone: (718) 960-8574. Fax: (718) 960-8584. E-mail: maantay@lehman.cuny.edu
This article is based on work supported (in part) by a grant from the City University of New York PSC-CUNY Research Award Program. The project title was "Mapping Asthma Incidence and Environmental Hazards in the Bronx in New York City."

Received 13 August 2001; accepted 14 January 2002.

not hosts to a hazardous waste facility, the host areas showed an unmistakable statistical and spatial correspondence to minority populations (*13*).

If "Toxic Wastes and Race" was the seminal study that helped propel the issue of environmental justice to the forefront of the public's consciousness in the late 1980s and early 1990s, it was certainly not the first environmental justice study. These issues have been researched extensively since at least the late 1960s, and study after study throughout three decades has shown the existence of disproportionate environmental impacts based on race and/or income (*14,15*). Since then, many other researchers have used mapping exercises to try to substantiate or refute the existence of environmental inequities.

In this article I review 13 GIS-based environmental equity studies conducted within the past decade (Table 1). In evaluating these studies, it is important to understand exactly what is being mapped, and how it is being measured.

Limitations of Mapping Environmental Justice Issues

Many environmental justice mapping studies conducted in the early to mid-1990s had definitional, conceptual, methodologic, and data problems, which limited their usefulness and raised questions as to the ability of GIS to assess environmental health or equity. Some of these concerns have since been at least partially addressed; others have not.

Is Injustice Predicted by Race or Class?

Some commentators have raised what may be termed philosophic questions, such as Can racism as a phenomenon be isolated? and Can discriminatory intent be proved? (*16,17*). Others have questioned whether environmental injustices are merely by-products of our market-based economy and due more to differences in land values than discrimination (*18,19*). We are not likely to reach consensus about these issues or effectively prove or disprove them.

Is income or race the deciding variable in exposure to pollution (*20*)? The findings of many environmental justice studies are in conflict on this very point: some clearly show race as the determining variable by controlling for income and still finding disproportionate burdens on minorities (*5,21*), whereas other studies control for race and find that income is the more statistically significant variable determining disproportionate environmental burdens (*22–24*).

In exploring which variable, race or economic status, is more important in predicting environmental injustices, some researchers have found that although it certainly is not the most affluent communities that bear the burden of pollution, it is not

Table 1. Summary of findings, methodologies, and data used in selected environmental equity studies, 1993–1999.

Name of study (year)	Type of environmental hazard	Scale (geographic extent of study)	Resolution (geographic unit of analysis)	Spatial coincidence method used	Proximity analysis used	Exposure index used	Dispersion modeling used	Disproportionate burdens found?
Burke, 1993 (*5*)	TRI	Los Angeles County, CA	Census tract	Yes	N/A	N/A	N/A	Yes, race and income
Perlin et al., 1995 (*23*)	TRI	United States	County	Yes	N/A	PEI, based on total pounds emissions/ population in county	N/A	Yes, race, but income inversely
Bowen et al., 1995 (*24*)	TRI	State of Ohio	County, with Cuyahoga County at tract level	Geographic unit with, without, or adjacent to hazardous facility	N/A	Toxicity index based on TLV and total pounds emissions	N/A	Yes, race in county and statewide but not in Cuyahoga County's tracts
Pollack and Vittas, 1995 (*21*)	TRI	State of Florida	Census block group	N/A	Natural log of distance to hazardous facility	N/A	N/A	Yes, race and income
Glickman and Hersh, 1995 (*6*)	TRI, EHS, power plants	Allegheny County, PA	Municipality, census tract, block group, and block	Yes; tract, block group and municipality	0.5-half mile and 1-mile buffers; plume buffers	Toxicity weights: RfD and potency carcinogens	ALOHA, ISCLT2, COMPLEX1 models	Yes, income in all methods; race in all buffers, not in all spatial coincidence
Centner et al., 1996 (*17*)	TRI	States of Georgia and Florida	Census block group	N/A	One-mile buffers	Percent of total pounds released based on areal assignment	N/A	Yes, income and race
Been and Gupta, 1996 (*22*)	TSDF	Nationwide, 544 communities	Census tract	Yes	N/A	N/A	N/A	Yes, race, but income inversely
Boer et al., 1997 (*26*)	TSDF	Los Angeles County, CA	Census tract	Yes, by range of tonnage per year	One-mile buffers for large capacity TSDFs	Tonnage per year (facility capacity)	N/A	Yes, race, but income nonlinear relationship
McMaster et al., 1997 (*54*)	TRI, Superfund, PetroFund, land recycling	Minneapolis-St. Paul, MN (citywide and neighborhood scale)	Census tract, block group and block	Yes; block group	100, 200, and 500 yards (for TRI only)	Pratt Index (chemicals weighted by pounds and toxicity index)	N/A	Yes, income and race for spatial coincidence, proximity analysis, and exposure index
Chakraborty and Armstrong, 1997 (*61*)	TRI	Des Moines, IA	Census block group	N/A	Circular buffers (0.5 and 1 mile) and plume buffers	N/A	ALOHA model	Yes, race and income in all buffers
Neumann et al., 1998 (*56*)	TRI	State of Oregon	Census block	N/A	Five buffers: 0.71, 1, 1.41, 1.73, and 2 miles (equal areas between circles); and tract centroid buffers	CI	N/A	Yes, race and income
Stretesky and Lynch, 1999 (*25*)	ACR	Hillsborough County, FL	Census tract	N/A	Distance from tract centroid to ACR	N/A	N/A	Yes, race and income
Sheppard et al., 1999 (*59*)	TRI, Superfund, PetroFund, land recycling	Minneapolis, MN	Census block group	Yes	Three buffers: 100, 500, and 1,000 yards; proximity ratio	N/A	N/A	Yes, income and race for both spatial coincidence and proximity analysis

Abbreviations: ACR, accidental chemical release; ALOHA, areal location of hazardous atmospheres; EHS, extremely hazardous substance; ISCLT2, industrial source complex long-term (model); PEI, population emissions index.

the poorest communities either (*25,26*). The relationship between income and proximity to environmental hazards is nonlinear, according to these studies, with the working-class locations more often hosting these facilities. The authors speculate about why this may be the case and suggest that the very poorest communities have so little economic activity that they are too poor to attract even a noxious facility. The most affluent communities have the economic and political power to successfully oppose such facilities from locating in their area. In these studies, however, race is still strongly associated with the locations of hazardous facilities.

Of course, the real issue is that minorities are disproportionately represented in the lowest economic subgroups. Race and low income are inextricably linked, and therefore it will be difficult to overcome the race/income confound in the base data (*27*). As concluded in the article "Environmental Racism in Southern Arizona":

> This research into the geopolitics of pollution finds that economics and race are inextricably intertwined. Those scholars who attempt to isolate economics from racism as causal factors in explaining environmental inequity, therefore, are missing the point. In fact, such efforts to tease out, for analytical purposes, the effects of each of these discrete variables on pollution impacts can itself be seen as a form of racism. Certainly, from the perspective of people of color having to deal with a dirtier environment, the effort to isolate class and race makes very little sense. (*8*)

Another angle that has been explored through GIS is that of which came first—the nuisance or the people. Been and Gupta (*22*) conducted a longitudinal study that looked at the population characteristics of the areas surrounding noxious facilities at the time the facilities were sited, and then every 10 years thereafter. The premise was if it could be shown that the minority population came to the area after the facility was in place, no discriminatory intent could be established and presumably there would be no environmental injustice in the siting. The problem with this line of reasoning is that it does not take into account that minorities are often very constrained as to where they are able to live, and is it not racism that restricts their choices to such undesirable places from which other people with more choice and money have fled?

As to the issue of discriminatory intent,

> We think it is irrelevant whether environmental injustice represents conscious racism, or classism, on the part of policy-makers, either now or in the past. Attempting to prove intent is a fool's errand, particularly when there are so many variables in the mix. What truly matters is how the problems are addressed by policy-makers and business interests in the present. In other words, who benefits from current siting and pollution control practices, and who pays the consequences? Further, how are these impacts affected by ongoing policies and enforcement practices? (*28*)

The concept of race operates on many levels to influence the potential for exposure to environmental hazards and disease. Race is often a proxy for other conditions that pose risks or exacerbate exposures. For instance, minority children suffer disproportionately from lead poisoning. Poor nutrition has been recognized as a contributing factor to childhood lead poisoning—nutritional deficiencies, especially in iron and calcium, increase children's susceptibility to lead toxicity. According to studies, minority children are more likely to be at greater risk of marginal nutritional status than White children (*29*). This is in addition to the fact that minority and low-income children are disproportionately exposed to lead in lead-based paints in older housing units as well as in high-traffic inner city areas where the contamination from lead-based gasoline still remains years after lead has been banned from gasoline.

Similarly, approximately 75% of the tuberculosis cases in the United States are people of color (*30*). Poverty, residential segregation by race, and housing overcrowding have been found to drive tuberculosis rates, and these factors disproportionately affect minorities. The discrimination experienced by minorities in the housing market may be emblematic of a whole range of conditions helping to make minorities more susceptible to tuberculosis (*31–33*). Thus, the context of race, rather than race itself, can be viewed as a risk factor.

Race and income, though the most prevalent indicators in the selection of disadvantaged populations for environmental justice research, should not be the only variables of concern. There are vulnerable populations other than the poor and minorities who may also be disproportionately at risk, such as the very young, very old, pregnant, immune compromised, infirm, and future generations. This poses difficulties in appropriately and comprehensively choosing the populations to study.

> African-American, Hispanic-, Native- and poor Americans seem to be the focus of attention. The young and the elderly should also be included. But should recent immigrant groups also be included? Or must they also be poor? In addition, consideration should be given to future generations. But how should future generations be represented? One way is by including aquifers and forest areas, salt-water swamps, and endangered species, all of which may be extremely important to future generations, as well as those already living. (*34*)

Environmental justice, in this more inclusive definition, would apply not only intragenerationally (equity for all people currently alive) but also intergenerationally, taking into account equity for future generations.

What Is Counted as a Hazard?

What types of facilities should be included in determining the existence of disproportionate environmental burdens? Many of the studies reviewed focus on only one set of hazardous land uses, such as transfer, storage, and disposal facilities for hazardous waste (TSDFs), Superfund sites, Resource Conservation and Recovery Act (RCRA) facilities, or Toxic Release Inventory (TRI) facilities (Table 1). This is done primarily because these types of facilities are registered and tracked on a national level, and consistent information is available on each facility, thus allowing valid comparisons to be made at the national level.

However, studying the impacts of only one set of facilities produces misleading and incomplete results. In many communities, the most egregious offenders are the small electroplating plants, auto-body welding shops, drycleaners, and waste transfer stations. These types of facilities are typically not required to register with the federal government, as are TSDFs or TRI facilities. The small polluters, which cumulatively may be creating more of an environmental burden than one large facility, are virtually unregulated and undetected. This makes mapping their impacts problematic. There is no database available for small geographic areas, and certainly none on a statewide or national level, making statewide and nationwide comparisons impossible. Most environmental equity mapping has been restricted to facilities that are on federal lists, because these lists are standardized and easily obtainable, but this just touches the tip of the iceberg as far as environmental burdens in many communities. Analyzing only the impacts of TSDFs or TRI facilities diminishes the magnitude of the total likely impact. Because of reporting deficiencies and lack of comprehensive data, total cumulative impacts from all noxious land uses within a given geography cannot be readily calculated.

An assumption that all noxious facilities are equally noxious is another source of problems in mapping environmental injustices. Many of the spatial analyses assume that one TRI facility, for instance, is equivalent to any other, but amounts of toxic emissions vary widely among TRI facilities, and emission levels and toxicity are often not mapped or factored into the analysis. Facilities in communities of color are typically worse polluters than those in White neighborhoods, receiving less regulatory enforcement and more lenient fines if discovered (*1,35*). These factors of difference are mapped more rarely, with many researchers focusing on simple counts of noxious facilities of one type or another or a binary measure of "facility" or "no facility" within a certain geography.

How Do We Determine Exposure Potential?

Spatial studies of environmental justice analyze the characteristics of the population potentially exposed to a hazardous land use. Exposure is often determined simplistically and defined as whether the population is in the same ZIP code, census tract, county, or municipal boundary as the noxious facility. This has the obvious drawback that one could live right across the county line from a facility just yards away, but for the purposes of the analysis would not be considered impacted by it, whereas one could live on the opposite side of the county miles away and still be considered impacted because of being within the same county as the facility. This becomes less of a problem for the finer geographic levels of analysis but is nonetheless not a very accurate way of characterizing the potentially impacted population.

In other analyses actual proximity to the facility is taken into account by constructing buffer zones of specified distances around the facility, capturing the demographic data for the entire population within the buffer regardless of what political or enumeration district they are in. The buffer zones are intended to act as surrogates for the areas of impact and are usually established as circles with a radius of one-half mile or 1 mile, or other appropriate distance, from the noxious land use.

Depending on which method is used, there can be substantial differences in estimating the magnitude and characteristics of populations affected by noxious land uses. Figures 1 and 2 illustrate the differences in the findings using the spatial coincidence method versus proximity analysis. The locations of permitted waste–related facilities in the Bronx, New York City, have been geocoded and overlaid on the census tract database (*36*). Figure 1 indicates the location of these facilities in relation to the percentage of population in each census tract that is "minority" (*37*). Figure 2 shows a comparison between the spatial coincidence method and proximity analysis in determining the potentially affected population. Using the demographic information for only those tracts housing a waste-related facility (spatial coincidence method) does not adequately capture the potential for exposure, as can be seen by the multitude of facilities on the edge of tract boundaries. Additionally, some tracts are very small, whereas some are very large, leading to a misrepresentation of the exposed population. Average household income was also calculated using the two methods, with similar results. When the locations of the Bronx TRI facilities are added to the waste-related facilities and population characteristics are calculated using the two methods, we again can see the differences in the numbers obtained (Table 2).

Proximity analysis is a more useful means of analysis, but it still does not definitively determine the potential for exposure.

> There is little known about the relationship between distance from a pollution source, such as a hazardous waste site, and actual health risks. . . . Accurate estimation of human exposures to hazardous air pollutants across all levels of geographic aggregation is constrained by the paucity of suitable monitoring methods, relevant ambient measures, and validated models for predicting exposures to populations of interest. (*23*).

Assumptions are also made that exposure risk is distributed equally within a given geography. The studies that try to account for risk based on distance assume that the risk a facility poses bears some relationship to proximity to the facility, an assumption that may be inaccurate in many cases.

> A better unit of analysis would be one that was based upon the actual distribution of the risk of the facility, which would depend on the type of substances the facility handled, wind patterns, the hydrology and geology of the site, transportation routes to the facility, and many other factors. (*22*)

Not only are these factors very complicated to assess, but data are often simply not available, or are not available in a uniform way for the entire study area and reference comparison areas. Other methods for determining exposure potential, such as dispersion modeling, are discussed below.

How Do We Measure Exposure?

A critical issue in these environmental justice studies is the lack of a reliable risk exposure index or proxy.

> [Previous studies] of environmental equity lack both a valid measure of the sources of pollution to which people may be exposed, and relatedly, a model that describes the relationship between proximity to those sources and the likelihood of exposure. (*21*)

Actual risk from TRI facilities, for instance, is dependent on many variables such as type of facility, substances emitted, quantities emitted, height of smokestack, exit velocity, wind direction and speed, pollution controls used, and topographic factors. Simple distance proximity equations are inadequate for measuring exposure.

> We found that risk-based evaluations can lead to different conclusions about environmental equity

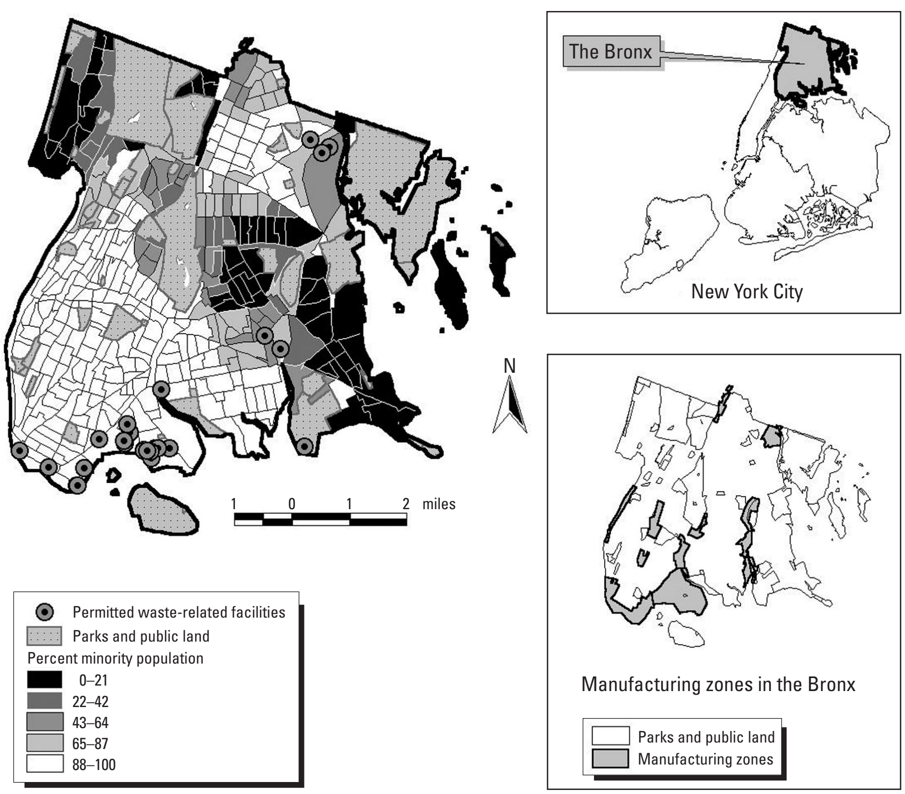

Figure 1. Distribution of waste-related facilities in relation to minority population, Bronx, New York. Data from U.S. Bureau of the Census (*85*), New York City Department of Sanitation (*86*), New York State Department of Environmental Conservation (*87*), and New York City Department of City Planning (*88*).

than proximity-based evaluations. The differences can be attributed to two principal factors. One is that the impact areas in risk-based evaluations are strongly influenced by the direction of the wind. The other is that the sizes of the impact areas in risk-based evaluations vary and are generally much larger than the circles used in proximity-based evaluations. (*6*)

The Geographic Unit of Analysis

The findings of some environmental justice mapping studies have been diametrically opposed to those of others. For instance, the nationwide study by Perlin et al. of TRI facilities at the county level shows a positive correlation between income and environmentally burdensome land use (*23*), with household income increasing in relation to the presence of TRI facilities, whereas the statewide study by Pollack and Vittas of TRI facilities in Florida at the census block group level shows a negative correlation (*21*), with household income declining in relation to the presence of TRI facilities. Many of these contradictions and discrepancies can be traced to the geographic unit of analysis used in the study, often referred to as the Modifiable Area Unit Problem (MAUP). Glickman and Hersh (*6*) show that altering the geographic boundaries of the study area has dramatic implications for the results of the analysis. In their study of industrial hazards in Allegheny County, Pennsylvania, they found that

> The choice of unit of analysis will affect even the most basic findings of an environmental equity study. Had we used only block groups to define 'community' we would have found contrary to expectations that in TRI communities the proportion of blacks and minorities is slightly lower than in non-TRI communities. Similar results hold for census tracts. This pattern is reversed, however, when we look at the proportions for the combined half-mile radius circles around TRI facilities vs. the areas beyond the circles. We also see that the proportion of blacks and minorities is substantially higher in municipalities with TRI facilities than in those without such facilities. (*6*)

Generally speaking, data aggregated at higher levels of governmental unit (county or city, for instance) will be less reliable as indicators of disproportionate burdens, and less accurate in identifying the affected populations, than data aggregated by smaller units such as census block groups or blocks. Because there is so much variation in demographics and facility location within the larger geographic units, impact and burden are impossible to determine, and comparison among geographic units becomes almost meaningless. Unfortunately, the availability of data is often what dictates the level of aggregation.

> To reflect a potential environmental health-based concept of risk, the boundaries should relate to exposure or risk from the site; however, a single boundary reflecting all variations in toxicity and contaminant fate and transport for each chemical present plus variabilities in the duration of human exposure and vulnerability would be virtually impossible…The scale of analysis chosen is often dictated by expediency, determined by how existing data bases are aggregated. . . . (*38*)

Therefore, the selection of the unit of analysis may, in fact, have little relationship to the actual geographic extent of exposure and risk, yet can shape the outcome of the analysis.

The Potential of GIS for Environmental Health and Equity Research

An effective public health management program demands an understanding of the spatial relationships between pollution and health.

> GIS can significantly add value to environmental and public health data in areas such as exploratory data analysis, hypotheses generation, confirmatory data analysis, and decision making. (*39*)

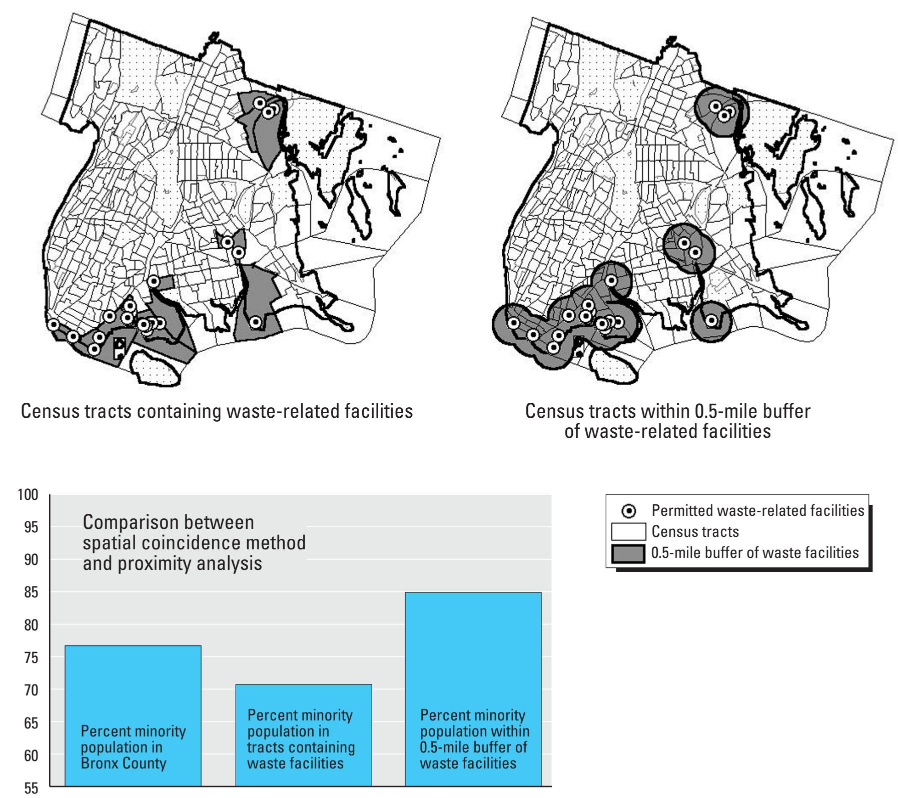

Figure 2. Comparison of spatial coincidence method and proximity analysis in determining the characteristics of the population affected by waste-related facilities. Data from U.S. Bureau of the Census (*85*), New York City Department of Sanitation (*86*), and New York State Department of Environmental Conservation (*87*).

Table 2. Comparison of spatial coincidence method with proximity analysis in determining characteristics of the population affected by hazardous facilities, Bronx, New York.

Geographic unit of analysis	Percent minority population (1990)	Mean household income (1990)
Reference population		
New York City (2,218 census tracts)	56	$41,700
The Bronx (355 tracts)	76	$29,200
Bronx manufacturing zones (97 partial tracts)	87	$25,200
Spatial coincidence method		
Tracts containing TRI facilities (16 tracts)	88	$24,600
Tracts containing waste-related facilities (14 tracts)	71	$35,400
Tracts containing TRI and/or waste facilities (24 tracts)	78	$31,500
Proximity analysis using buffers:		
Tracts within 0.5-mile buffer of TRI facilities (67 partial tracts)	88	$25,800
Tracts within 0.5-mile buffer of waste facilities (39 partial tracts)	87	$26,200
Tracts within 0.5-mile buffer of TRI and/or waste facility (75 partial tracts)	88	$24,600

For instance, mapping disease rates geographically and temporally may shed light on previously unrecognized patterns, which will suggest answers, or at least provide a focus and direction for further study. GIS can also be used to select case study areas meeting specific criteria and to create and test hypotheses relating to environmental risk factors. GIS can combine health outcomes on the individual level with exposure data aggregated at the geographic unit level (census tract, health district, etc.) and then model potential exposures, for use in overlaying the disease incidence data (*40*).

Although health outcomes were not a specific part of the studies reviewed, GIS-based environmental equity research nevertheless provides a valuable tool for health professionals. Decision making and policy formulation are enhanced by spatial information. Identifying the population likely to be affected by environmental burdens allows more effective educational intervention and the planning of health care delivery systems (*41*). It may also help point out the geographic areas where health assessments should be a priority.

Integration of Modeling and Statistical Software with GIS

Some of the problems in using GIS for environmental health and equity research are due to software deficiencies such as the lack of complex environmental modeling functions integrated within GIS programs. Having to use external modeling applications is more cumbersome for the researcher and limits the role of GIS to primarily data organization and storage, data exploration, and display (*42*). This situation could be improved, however, if the software developers had a demand to respond to. As more researchers use GIS in their work, it will be easier to justify the costs of development to integrate GIS and modeling software.

This integration has already occurred to a substantial degree with GIS and complex geostatistical functions. Many geostatistical functions have been incorporated into a number of major GIS software packages or are available as extensions (separate add-ons to mapping programs). For instance, the Spatial Analyst extension is available for ArcView 3.x software (*43*), and both Spatial Analyst and ArcGIS Geostatistical Analyst have resident spatiotemporal analytic tools. These include Inverse Distance Weighting and Spline methods of spatial interpolation on point data, enabling estimates of data values at unsampled locations (*44*). Point data might represent air monitoring sites; facilities emitting pollution; soil, air, or water sample locations; or ZIP code centroids with disease rates attached. Kriging, a linear interpolation method, is available in ArcView through an Avenue script (prewritten applet in the programming language native to ArcView 3.x). Kriging allows predictions of unknown values of a random function from observations at known locations by using a model of the covariance of the random function and accommodating and estimating the underlying trend (*45*).

Spatial regression and geostatistical models can also be employed by using specialized software such as S+ Spatial Stats, which has been designed by a software developer (*46*) to interface almost seamlessly with the ArcView 3.x software (*47*). Scripts written by individuals and widely accessible via user group web sites can also be used directly with industry-standard mapping packages to perform cluster analysis such as K-function and Gi* statistics (*48,49*). The ease of surface modeling using these built-in and loosely-coupled local and global interpolators will change the way we measure and predict environmental burdens and greatly improve the speed and efficiency of data exploration.

Building Better Databases

The real constraint in using GIS for health and equity research is not software, however, but data deficiencies. Incomplete, inaccurate, and nonexistent information does not necessarily reflect our state of knowledge about the issues but may be merely an indication of our society's informational (and funding) priorities.

For instance, it is virtually impossible to create a measure of exposure and risk without more detailed and careful data on actual emissions and ambient conditions. Analysis must be able to take into account measured quantities to estimate cumulative impacts from multiple sources of pollution and synergistic impacts from combining pollutants. Studies that investigate exposure to only one type of hazard are not helpful in determining the full extent of the impacts. Many of the databases relied upon by researchers, such as TRI, are notoriously inadequate for detailed modeling. TRI information is self-reported by the facilities and is based on estimated emissions not measured quantities (*50,51*). Some researchers compound the errors by aggregating releases to soil, water, and land as one quantity of raw pounds, although the effects on human health and the environment differ markedly by media.

Reliable health assessments are necessary for environmental health and equity research to progress to the next level. Issues such as patient confidentiality, lack of data sharing among hospitals, private doctors, and other health care providers, and few mandatory reporting mechanisms all conspire against comprehensive health databases. There is no national registry database for chronic diseases such as asthma, for example.

GIS analysis has been less successful (or less well used) in addressing issues such as population mobility, occupation, and genetic predisposition, although these all potentially play a role in the relationship between exposure and health. An understanding of population mobility, for example, is crucial to tracking the environmental exposures over time of susceptible populations, but databases detailing population movement have not been widely developed. An index of residential neighborhood stability could be created for community comparison purposes, but this would be of limited value in monitoring spatial correspondence of specific hazards and health outcomes. Some of the same data deficiency problems exist for attempts to spatially link occupation and health hazards and to monitor specific populations by residence location.

For relatively small geographic areas, however, it is possible to develop something approaching a comprehensive hazards database and to perform a more complete health and population survey. In the Greenpoint-Williamsburg community of Brooklyn, New York, publicly available environmental databases were assembled into a GIS, then supplemented with local knowledge bases, such as a detailed lot-by-lot land use inventory, and updated regularly to keep the data current (*52,53*). Because many hazardous facilities are not tracked at a national, statewide, or municipal level, community-led inventories and monitoring of local conditions are essential in assessing environmental loads.

Development of an Exposure Index

Several environmental health and equity studies have employed an exposure index to reflect some quantification of a population's risk from environmental burdens beyond simply proximity to or presence of a hazardous facility. In earlier studies exposure was often a measure of facility capacity, such as tons per year of hazardous waste handled (*26*) or total pounds of pollutants released per year, divided proportional to area in the geography of concern (*17*) or divided among the potentially affected population [as in the Population Emission Index of Perlin et al. (*23*)].

The total quantity of chemicals handled or released by a facility does not directly correspond to health impacts, however. Bowen et al, in their study of TRI facilities in Ohio (*24*), took into account not only the number of raw pounds of chemicals released but also pounds adjusted for toxicity, using Threshold Limit Values (TLVs). Although TLVs are available for many of the chemicals on the TRI list, it remains a somewhat problematic index for health and equity assessments, generally having been developed and used to gauge occupational safety among a healthy worker population. It is unknown how well this index estimates hazard for more vulnerable populations such as children, the elderly, pregnant women, and the immune compromised.

The study of hazardous facilities in Minneapolis, Minnesota, by McMaster et al. (*54*) refined the measurement of exposures. After ranking and mapping facilities by proportional symbols according to total chemical poundage released per year, they applied the Pratt Index, which compares chemicals based on their environmental behavior and toxicity by calculating a ratio of potential exposure to toxicity (*55*). This study found that minority groups and poor people were not only more likely to live in proximity to hazardous land uses, but were also burdened by a higher concentration of such facilities, with a higher level of exposure to toxic substances.

In a study of TRI facility impacts in Oregon, Neumann et al. (*56*) used a media-specific Chronic Toxicity Index (CI), which incorporates chronic oral toxicity factors for carcinogens and noncarcinogens to estimate and compare relative hazards from TRI releases. Although not useful for identifying population or individual risk, it is an excellent preliminary screening method.

> The ranking of TRI emissions using the CI combined with knowledge about the demographics of the communities at risk of exposure such as population density, race, ethnicity, socioeconomic status, and age is an attempt to help set priorities for future risk or public health assessments, epidemiological studies, and basic research on cellular mechanisms associated with environmental health problems. (*56*)

The limitations of data restrict the completeness of the CI as a measure of exposure. The CI is based on oral toxicity because inhalation reference doses for TRI chemicals are not available. However, inhalation reference concentrations would obviously be more useful in estimating hazard from TRI air releases. The CI also does not measure acute toxicity, which would be useful in identifying populations at greatest risk from industrial accidents.

To be more meaningful, an exposure index should reflect an estimate of total environmental loads resulting from all types of pollutants, i.e., a cumulative load index. Theoretically, any given location could be assigned a number indicating the total environmental load borne by people in that geography. A weighting and ranking index could be developed with a unit of measurement based on toxicity and concentration of each pollutant, weighted for severity of potential impact from exposure. This methodology, although useful in a planning and policy context, would be of more limited use for regulatory and enforcement purposes, given the structure of current laws, as it is not based on existing legal standards. However, the cumulative impact index would take into account effects of pollutants that individually may not exceed thresholds but when considered together may constitute an impact to human health (*57*). Linking the cumulative load model to the GIS would allow visual inspection of the spatial distribution patterns and complex spatial analyses to be performed and result in a block-specific score of carcinogenic and noncarcinogenic pollutant loads.

Development of an aggregate environmental load index would be of value in establishing baseline profiles of communities for comparative purposes and documenting the relative environmental loads of various communities. The aggregate environmental load index would also allow communities with the highest environmental loads to be targeted for pollution prevention and remediation programs and enable examination of the correspondence between incidence of environmentally linked diseases and environmental loads. GIS could also facilitate research into the synergistic effects of toxic substances by pinpointing the geographies subjected to such environmental loads and comparing them with known or suspected health problems in these areas.

Clearly, further refinements in exposure indices will help estimate potential for health effects from hazardous facilities. An index that incorporates not only a toxicity factor but also information about persistence and environmental fate of toxic chemicals such as discussed by Jia and Di Guardo (*58*) will advance GIS-based health and equity research significantly.

Advanced Proximity Analysis, Dispersion Modeling, and Fate and Transport Simulation

In addition to exposure indices reflecting toxicity and other measures of impact, advances have been made in more precisely identifying the geographic extent of the exposure from hazardous facilities. These methods include dispersion modeling of airborne pollution and flow and transport modeling of contaminants in subsurface media, as well as more advanced methods of proximity analysis.

For instance, Sheppard et al. (*59*), in a study of the distribution of hazardous land uses in Minneapolis, Minnesota, developed a Proximity Ratio that was used with both the spatial coincidence and buffering methods to determine affected populations. The ratio was computed by dividing poverty rates for specific population groups in geographies containing a hazardous facility by poverty rates for that group in geographies without such a facility. A high proximity ratio means that a particular group living near a hazardous facility is more likely to be in poverty than the equivalent nonproximate group. They found that for all groups studied (African Americans, Latinos, Native Americans, non-Hispanic Whites, and children under the age of 5 years) proximity ratios exceeded 1, meaning that people within certain distances of a hazardous facility are more likely to live in poverty than their counterparts outside the buffers or census tracts containing the facilities.

To make sure these ratios reflect a true significance and do not occur just by chance, a randomization routine was run on the TRI location data. Through Monte Carlo simulation, 1,500 possible locations for the TRI facilities were generated to test whether the pattern of higher poverty rates near hazardous facilities was coincidence and if these high poverty rates would be observed if TRI sites had been located randomly within Minneapolis. The proximity ratios were found to be unusually high compared with those that might have resulted by chance.

Another technique used to improve the assessment of impacted areas and populations is detailed in the study by Neumann et al. (*56*). In addition to buffering facilities and estimating exposure of populations within the TRI buffers using the CI, as mentioned above, they also buffered the census tract centroids. By doing this they were able to capture information on populations exposed to multiple sources of pollution by aggregating emissions from all facilities within the centroid buffers. This is an important consideration in dense urban areas where hazardous facilities may be close to other hazardous facilities and proximate populations are at risk from exposures to emissions from multiple facilities. This yields a more realistic estimation of actual exposure.

Provided that detailed facility information is available, dispersion modeling may offer the best means of determining the geographic extent and severity of exposure. By using mathematic models executed externally to GIS, the spatial patterns of the average annual concentration of each pollutant emitted to the air by a hazardous facility can be estimated. Glickman and Hersh used a variety of models developed by the U.S. Environmental Protection Agency (U.S. EPA) and the National Oceanic and Atmospheric Administration (NOAA) in their study of hazardous facilities in Pennsylvania (*6*). The Areal Locations of Hazardous Atmospheres (ALOHA) model

(*60*), for instance, was used to determine the worst-case chemical in each facility, i.e, the one with the longest plume. A probability distribution of wind speeds and directions was factored in to create a probable impact area for each facility, creating a plume buffer that was brought into the GIS and overlaid on the census data (similar to circular buffers used in other studies) to determine the characteristics of the exposed populations. Plume extent was combined with dose–response rates to yield risk estimates (average individual risks) measured in terms of the per capita expected number of premature deaths in a lifetime. The analysis used two factors to form a toxicity weight: a measure of potency for carcinogens, and reference dose (RfD), a measure for noncarcinogens. The total volume of emissions was multiplied by the toxicity weight to derive a hazard rating.

Dispersion modeling was also used in research by Chakraborty and Armstrong in Des Moines, Iowa (*61*). The racial and economic characteristics of the populations exposed to toxic releases from TRI facilities based on various circular buffers were compared with those within plume buffers obtained through dispersion modeling. A composite plume buffer was developed based on the largest chemical release at each facility and averaged weather conditions. Their research found that a larger proportion of minorities and people below the poverty line live within the plume buffers compared with the circular buffers.

A public health assessment study being conducted by the Agency for Toxic Substances and Disease Registry (ATSDR) is using air dispersion modeling integrated with GIS to determine the geographic extent of exposure and the demographic characteristics of the population affected by two phosphate-processing plants near an American Indian reservation in Idaho (*62*). Using the U.S. EPA industrial source complex model, particulate matter (PM) emissions will be modeled based on specific information about area topography and meteorology. This will produce concentration isopleths (contour lines) of particles smaller than 2.5 µm in diameter ($PM_{2.5}$—those of greatest health concern because they can penetrate the sensitive areas of the respiratory tract). These isopleths will be imported into the GIS and transformed into concentration polygons, which will be overlaid with census data. The overlay analysis will clip the demographic information of people who have been exposed to $PM_{2.5}$ above the health-based standard, reflecting the concentration polygons predicted by the air dispersion modeling. The demographic data about total population exposed, total susceptible populations exposed, and the socioeconomic status of persons exposed will be obtained and compared with address-geocoded mortality data for respiratory and cardiopulmonary deaths. By performing a point-in-polygon analysis, it can be determined if the geocoded addresses for the deaths are within the polygons representing a geographic area where people have been exposed at levels of health concern.

The report concludes with a number of cautions about the proposed methodology, and the limitations of GIS and air dispersion models in exposure assessments:

> The problems of areal interpolation and the fallacy of the homogeneous polygon must also be considered carefully when evaluating the method used to determine the demographics of the exposed population defined by the air dispersion model. The polygons that define the various exposure levels predicted by the air dispersion model will not correspond to the US Census Bureau's reporting units (e.g., census tracts or block groups, etc.). Furthermore, the populations within the census units are not evenly distributed. Therefore, an overlay analysis method that does not provide some estimate of the population densities within each census unit will likely produce much exposure misclassification. ATSDR uses an area proportion program (a script written in Avenue, the programming language of ArcView GIS [ESRI, Redlands, CA]) that is good for many applications; however, it assumes that a population within a given census reporting unit is evenly distributed. . . . Other estimates are being evaluated that provide better estimates of population densities within the census reporting units. The two methods currently being evaluated are the kernel density method and the census control method. Both of these methods use techniques that "disaggregate" the census reporting units, helping to alleviate the areal interpolation problem and avoid the fallacy of the homogeneous polygons. . . . An ecologic study design based on a GIS analysis carries with it unique methodological issues beyond those that may be encountered in other epidemiologic designs. Ecologic fallacy, disease and exposure misclassification, and control for confounding must be carefully considered when designing an ecologic study and in interpreting its results. (*62*)

In "Establishing Links between Air Quality and Health: Searching for the Impossible?", Dunn and Kingham outline some of the problems associated with dispersion modeling (*63*). The models require detailed inputs about emissions and facilities that may not be available or accurate, and they rely on assumptions about meteorologic and topographic conditions that may not reflect reality. Small differences in terrain and building configurations can affect the behavior of airborne contaminants, and these fine differences are difficult to represent adequately in a model. Additionally, most of the models are based on point-source pollution (from a smokestack) and do not take into account fugitive emissions (from non–point sources) or pollution from linear sources such as roads. Results of dispersion modeling should therefore be treated with caution.

GIS have also been used to assess fate and transport of contaminants in the subsurface environment. As with air dispersion modeling, groundwater flow models are generally executed outside the GIS environment, with results brought into the GIS in the form of contaminant concentration isopleths, which are then overlaid with the demographic data to assess the extent and characteristics of the exposed population. An exposure assessment case study conducted by ATSDR attempted to link contamination from environmental sources with increased health risk to humans (*64*). In "Exposure Assessment of Populations, Using Environmental Modeling, Demographic Analysis, and GIS," an external mathematic model using a finite-element Galerkin procedure provided the researchers with contours delineating the geographic extent of groundwater contamination from trichloroethylene released from an industrial facility (*64*). Various groundwater modeling and simulation techniques are well established, and those used in this study include steady layered aquifer model and contaminant transport in layered aquifer media, which were run to simulate different scenarios based on various assumptions about contamination levels and remediation plans. Because the industrial plant had continued to contaminate the groundwater for more than 20 years, and nearby residences were eventually connected to town water supplies and thereafter presumably no longer exposed to the contaminants in the groundwater, the study had a temporal as well as a spatial component.

By integrating the results of the modeling with the GIS and demographic databases, the researchers were able to obtain a snapshot of the exposed populations. However, because this was a longitudinal study exploring exposures over time, population mobility is a factor in assessing human health impacts. Availability of additional demographic information on the distribution and mobility of households would facilitate the generation of more precise spatial and temporal exposure patterns that could easily be accommodated by methodology described by Maslia et al. (*64*). As with many of the other studies discussed, the lack of key data is a prime impediment to precision and accuracy in exposure assessments.

Conducting Neighborhood-Scale Analyses

Most environmental health and equity studies have been conducted at the national, statewide, regional, or city level of analysis, as evidenced by the majority of studies reviewed in this paper. Because of the volume and type of data required to accurately inventory and assess existing conditions and to model future conditions, it is likely that neighborhood- or community-level analysis will be more feasible and useful than studies of larger geographic extents. By definition, studies covering larger geographies use coarser-resolution data and cannot pinpoint as accurately the spatial patterns and connections that may exist.

Neighborhood-scale studies also have the advantage of being able to incorporate local knowledge bases, which can be used to augment (and verify the accuracy of) publicly available data sources on environment and health. For instance, communities can inventory the locations of hazardous facilities that do not appear on any state or national list, such as drycleaners, solid waste-related facilities, junkyards, auto bodyshops, small industrial facilities that fall beneath the reporting thresholds for TRI, or coal-burning schools, as well as confirm and cross-check the locations and types of facilities listed by governmental permitting agencies. It is also less complex to aggregate exposures from multiple and varied sources of pollution at a neighborhood scale, and more likely that necessary informational inputs can be obtained in a comprehensive way for modeling purposes. The locations of sensitive populations such as schools, day care centers, hospitals, and nursing homes can also be more accurately mapped and quantified at the neighborhood scale. There is the potential for using geodemographic data at a finer resolution, as the census data can be supplemented in many cases by data collected by the city's planning department or by community data bases. McMaster et al. discuss using GIS to identify, map, and monitor potential environmental hazards in four Minneapolis neighborhoods (*54*):

> Neighborhood-scale analysis and mapping holds great promise for assisting communities in identifying risks posed by environmental hazards to different social groups in their neighborhood and for the development of more detailed, complete, and positionally accurate information by incorporating 'local knowledge' into the GIS database. (*54*)

Perhaps the most important benefit of neighborhood-scale analysis is the potential for direct involvement of the affected people and the intimate knowledge of their surroundings that they bring to the project, along with the sense of ownership that their involvement with the project brings to them (*65*).

Community-based GIS projects have been instrumental in advocacy work and have proved effective in contributing to community organizing, data collection and documentation of land use, public health, and environmental conditions of low-income neighborhoods and communities of color for purposes of influencing policy and planning decisions. The New York City Environmental Justice Alliance (NYCEJA) is an example of a nonprofit organization using GIS to promote environmental justice:

> Our vision of technical assistance is not an end, but a means for building our collective capacity to fight against environmental discrimination. . . . [D]isparate environmental conditions are often disregarded by policy makers. Documenting the environmental conditions in underserved communities is important because data is often out of date, inaccessible, or not available for these areas. NYCEJA strives to not only assist its members collect and analyze data, but it also ensures that grassroots communities are directly involved in the entire process and to advocate for themselves. (*66*)

Implications of Policy and Planning Decisions on Environmental Health and Equity

Most environmental equity studies are based on the locations of specific hazardous facilities. Not only must we prepare more comprehensive analyses based on multiple sources of pollution, but we must also consider other factors in the potential for exposure and disproportionate burdens. We need to be concerned not only with the location of existing and past hazardous land uses and the siting of such facilities disproportionately in poorer neighborhoods and communities of color but also with the distribution of locations having the potential to house hazardous facilities.

My own research on industrial zoning changes and environmental justice in New York City indicates that the reasons for disproportionate concentrations of noxious land uses go deep into underlying policies and assumptions (*67,68*). In New York City, as in many other places with zoning regulations, noxious facilities can be located only in areas zoned for manufacturing (M zones), and M zones tend to be located primarily in or near neighborhoods where residents are poorer than average and have a higher-than-average likelihood of being African American, Latino, or other minority. This obviates the principles of the city's Fair Share guidelines (*69*), which were intended to ensure that the burdens of urban (post-) industrial life be shared equally and not fall disproportionately on any group or area.

This inequitable state of affairs in New York City is perpetuated by city planning practices and policies that continue to decrease the areal extent of industrial zones in more affluent and less heavily minority neighborhoods while increasing the areas of industrial zones in poorer and more heavily minority neighborhoods. This serves to further concentrate noxious land uses within predominantly poor and minority communities. Because this situation likely is not unique to New York City, zoning and other planning policies and practices must be taken into account when evaluating exposure and risk from hazardous land uses.

Ultimately, any siting of hazardous activities may lead to unjust exposures. The idea that we can solve the problem of disproportionate toxic exposures by spreading the pollution around more equitably is absurd. Many believe the real solution is to be found in eliminating or sharply reducing the need for many of these noxious facilities to exist (*70*). This, of course, will require structural changes in patterns of consumption, waste production and disposal, transportation, and community governance, planning, and policy making. There have been instances, however, where "Not In My Back Yard" has become "Not In Anybody's Back Yard," thereby forcing government and industry to evaluate broader issues, including "the propriety of a production system under private control where, in the quest for profit, the public is exposed to known risks" (*71*). Another aspect of the long-term solution is to make noxious facilities less harmful, by pollution prevention techniques, source reduction of toxic substances, strengthened and evenly applied enforcement of environmental regulations, and equitable remediation of hazardous conditions.

Making the Connection between Environmental Justice and Environmental Health

Although showing environmental inequity regarding the distribution of noxious facilities is certainly of consequence, especially in combating future inequities, it is probably more critical at this point to demonstrate linkages between environmental burdens and adverse health impacts. Only when the spatial correspondence is clear can public health and environmental protection officials, the medical research community, health care providers, and pollution prevention scientists begin to develop solutions to existing environmental injustices and resulting health effects. People within communities disproportionately burdened with pollution are suffering adverse physical and psychologic impacts, as well as economic impacts, according to a wealth of anecdotal reports and empirical research (*28,72–81*). It is important to show the disproportionate effects of pollution rather than just the fact that disproportionate distribution of pollution sources exists.

There are encouraging precedents for positive results stemming from such research and subsequent actions based on the research. For instance, studies from the 1970s suggested that the high rate of childhood lead poisoning in inner cities, disproportionately affecting minority and low-income children, was connected to the high traffic volumes in these areas and the concomitant exposure to lead-based gasoline emissions (*82*). In large measure because of these findings, lead in gasoline was phased down by U.S. EPA regulation in the 1980s, and thereafter the rate of childhood lead poisoning dropped dramatically, demonstrating the potential for reducing unjust environmental exposures (*83*).

A more recent example is given in the paper "Impact of Changes in Transportation and Commuting Behaviors during the 1996 Olympic Games in Atlanta on Air Quality and Childhood Asthma," which shows that childhood asthma events were significantly reduced in the 17-day period when vehicular traffic was curtailed in the metropolitan area because of the Olympic Games of Atlanta (*84*). Concomitant changes in air quality were also examined and compared with the 4 weeks preceding and following the games. Peak daily ozone concentration decreased nearly 28%, peak weekday morning traffic counts dropped nearly 23%, and the number of asthma acute-care events decreased 44% during the Olympic Games. This indicates that the decreased traffic density was "associated with a prolonged reduction in ozone pollution and significantly lower rates of childhood asthma events"(*84*). However, such clear-cut cases of spatial correspondence and causality are unfortunately rare.

Tracing the evolution of GIS-based environmental equity research has shown that although refinements in methods and techniques have been made, in most cases we are still far from producing conclusive spatial correlations. Nevertheless, the bulk of the research, from the most basic binary studies of presence or absence of a hazard to the more sophisticated exposure indices, modeling, and statistical analyses, have all tended to find a disproportionate environmental burden upon the nation's poor and minority populations. Because of the lack of comprehensive data and the conservative nature of the methods used in these studies, there is a great likelihood that the disproportionate burden has been vastly underestimated.

References and Notes

1. Bullard RD, ed. Unequal Protection: Environmental Justice and Communities of Color. San Francisco:Sierra Club Books, 1994.
2. Johnston BR, ed. Who Pays the Price? The Sociocultural Context of Environmental Crisis. Washington, DC:Island Press, 1994.
3. Bryant B, ed. Environmental Justice: Issues, Policies, and Solutions. Washington, DC:Island Press, 1995.
4. United Church of Christ's Commission for Racial Justice. Toxic Wastes and Race in the United States: A National Report on the Racial and Socio-Economic Characteristics of Communities with Hazardous Waste Sites. New York:United Church of Christ, 1987.
5. Burke LM. Race and environmental equity: a geographic analysis in Los Angeles. Geogr Info Sys 3:44–50 (1993).
6. Glickman TS, Hersh R. Evaluating Environmental Equity: The Impacts of Industrial Hazards on Selected Social Groups in Allegheny County, Pennsylvania. Discussion Paper 95-13. Washington, DC:Resources for the Future, 1995.
7. Maantay JA, Timander L, Graziosi G, Meyers L. The Bronx Toxic Release Inventory Report. New York:Center for a Sustainable Urban Environment/U.S. Environmental Protection Agency, Region 2, 1997.
8. Clarke J, Gerlak A. Environmental racism in southern Arizona. In: Environmental Injustices, Political Struggles: Race, Class, and the Environment (Camacho DE, ed). Durham, NC:Duke University Press, 1998.
9. On websites such as *http://www.epa.gov/enviro* (The U.S. Environmental Protection Agency); *http://www.hud.gov/emaps* (The U.S. Department of Housing and Urban Development's environmental maps); *and http://www.cmap.nypirg.org* (The New York Public Interest Research Group), you can select your geography of interest and map out various locations, including hazardous facilities, public projects, and brownfields. With some websites, such as *http://www.hud.gov/emaps,* you can view the demographic and socioeconomic characteristics of the proximate populations.
10. Dorling D, Fairbairn D. Mapping: Ways of Representing the World. Harlow, UK:Addison, Wesley, Longman, Ltd., 1997.
11. Wood D. The Power of Maps. New York:Guilford Press, 1992.
12. Some of these issues were previously discussed, and six of the studies were evaluated in more detail in Maantay JA. An Evaluation of Recent Environmental Justice Research. Discussion Paper. New York:Center for Sustainable Urban Environment, 1996.
13. The term *minority population* refers to the population that is not non-Hispanic white. Many people consider the term *minority* to be a misnomer, because in many U.S. urban areas, such as New York City, as well as in certain rural areas, people classified as minorities actually constitute the majority.
14. According to a 1993 examination of over 50 studies of the distribution and siting of environmental hazards conducted between 1967 and 1993, about 90% of the studies found a racial disparity, about half found a racial and income disparity, with all of them finding a racial or income disparity. Goldman BA. Not Just Prosperity: Achieving Sustainability with Environmental Justice. Washington, DC: National Wildlife Foundation, 1993.
15. White HL. Race, class, and environmental hazards. In: Environmental Injustices, Political Struggles: Race, Class, and the Environment (Camacho DE, ed). Durham, NC:Duke University Press, 1998.
16. Pulido L. A critical review of the methodology of environmental racism research. Antipode 28(2):142–159 (1996).
17. Centner T, Kriesle W, Keeler AG. Environmental justice and toxic releases: establishing evidence of discriminatory effect based on race and not income. Wisconsin Environ Law J 3(2):119–158 (1996).
18. Been V. Locally undesirable land uses in minority neighborhoods: disproportionate siting or market dynamics? Yale Law J 103:1383–1422 (1994).
19. Hamilton J. Testing for environmental racism: prejudice, profits, political power? J Policy Anal Manage 14:107–132 (1995).
20. Mohai P, Bryant B. Environmental injustice: weighing race and class as factors in the distribution of environmental hazards. Univ Colorado Law Rev 63:921–932 (1992).
21. Pollock PH, Vittas ME. Who bears the burden of environmental pollution? Race, ethnicity, and environmental equity in Florida. Social Sci Q 76(2):294–309 (1995).
22. Been V, Gupta F. Coming to the nuisance or going to the barrios? A longitudinal analysis of environmental justice claims. Ecology Law Q XXIV(1):1–35 (1996).
23. Perlin SA, Setzer RW, Creason J, Sexton K. Distribution of industrial air emissions by income and race in the United States: an approach using the toxic release inventory. Environ Sci Technol 29(1):69–80 (1995).
24. Bowen WM, Salling MJ, Haynes KE, Cyran EJ. Towards environmental justice: spatial equity in Ohio and Cleveland. Ann Assoc Am Geogr 85(4):641–663 (1995).
25. Stretesky P, Lynch MJ. Environmental justice and the predictions of distance to accidental chemical releases in Hillsborough County, Florida. Social Sci Q 80(4):830–846 (1999).
26. Boer JT, Pastor M Jr, Sadd JL, Synder LD. Is there environmental racism? The demographics of hazardous waste in Los Angeles County. Social Sci Q 78(4):793–810 (1997).
27. Faber D, ed. The Struggle for Ecological Democracy: Environmental Justice Movements in the United States. New York:Guilford Press, 1998.
28. Timney M. Environmental injustices. In: Environmental Injustices, Political Struggles: Race Class, and the Environment (Camacho DE, ed). Durham, NC:Duke University Press, 1998.
29. Mahaffey KR. Nutrition and lead: strategies for public health. Environ Health Perspect 103(suppl 5):191–196 (1995).
30. Center for Disease Control and Prevention. Available: *http://www.phppo.cdc.gov/phtn/tbmodules* [accessed 28 December 2001].
31. Stephens C. Healthy cities or unhealthy island: The health and social implications of urban Inequality. Environ Urban 8(2):9–30 (1996).
32. Drucker E, Alcabes P, Bosworth W, Sckell B. Childhood tuberculosis in the Bronx, New York. Lancet 343:1482–1485 (1994).
33. World Health Organization. Groups at Risk: WHO Report on the Tuberculosis Epidemic 1996. Geneva:WHO, 1996.
34. Greenberg M. Proving environmental inequity in siting locally unwanted land uses. J Risk - Iss Health Saf 4(3):235–252 (1993:251).
35. Lavelle M, Coyle M. Unequal protection: the racial divide in environmental law. Nat Law J 15:S1-S2 (1992).
36. Waste-related facilities included in the study (shown on the maps in Figures 1 and 2) are primarily privately owned and include solid waste transfer stations and/or processing facilities for putrescible waste, construction and demolition materials, paper and other recyclables, fill materials, regulated medical waste, yard waste and composting, and sludge. These facilities are permitted by the New York City Department of Sanitation and/or the New York State Department of Environmental Conservation. There are many other waste-related facilities in the Bronx, New York City, that are not permitted or registered by these agencies and are not shown on the map but that are required by the New York City Zoning Resolution to locate within a manufacturing zone.
37. Based on the 1990 census definitions and the guidelines established in Federal Statistical Directive No. 15 issued by the Office of Management and Budget in 1992, which provides standards on ethnic and racial categories for statistical reporting to be used by all federal agencies, this study used a derived variable of minority. This category is a summation of the Hispanic, non-Hispanic black, Non-Hispanic American Indian, non-Hispanic Asian or Pacific Islander, Eskimo or Aleut, and non-Hispanic other race categories. Other federal agencies, such as the U.S. Environmental Protection Agency, construct a similar minority category as above for their research on environmental justice issues. Each decennial census defines racial and ethnic categories differently, making cross-census comparisons difficult. The guidelines and standards for racial and ethnic classification were revised by the Office of Management and Budget in 1999, and the 2000 census uses a markedly different classification system from the previous censuses.
38. Zimmerman R. Social equity and environmental risk. Risk Anal 13(6):649–666 (1993).
39. Tim US. The application of GIS in environmental health sciences: opportunities and limitations. Environ Res 71:75–88 (1995).
40. Vine MF, Degnan D, Hanchette C. Geographic information systems: their use in environmental epidemiologic research. Environ Health Perspect 105(6):598–605 (1997).
41. Scholten HJ, de Lepper MJC. The benefits of the application of geographical information systems in public and environmental health. World Health Stat Q 44(3):160–170 (1991).
42. Steyaert LT. A perspective on the state of environmental simulation modeling. In: Environmental Modeling with

GIS (Goodchild MF, Parks BO, Steyaert LT, eds). Oxford:Oxford University Press, 1993;16–30.

43. Environmental Systems Research Institute, Inc. ArcView GIS Software, Version 3.2. Redlands, CA:ESRI, 1999.
44. Environmental Systems Research Institute, Inc. Working with ArcView Spatial Analyst. Redlands, CA:ESRI, 1998.
45. Isaaks E, Srivastava RM. An Introduction to Applied Geostatistics. Oxford:Oxford University Press, 1989.
46. Insightful Corporation. S+ Spatial Stats Advanced Spatial Analysis Software, Version 1.5. Seattle, WA:Insightful Corp., March 2000.
47. Kaluzny SP, Vega SC, Cardoso TP, Shelly AA. S+ Spatial Stats: User Manual for Windows and UNIX. New York:Springer-Verlag, 1998.
48. Fotheringham AS, Brunsdon C, Charlton M. Quantitative Geography: Perspective on Spatial Data Analysis. London:Sage Publications, 2000.
49. Getis A, Ord JK. Local spatial 6tatistics: an overview. In: Spatial Analysis Modeling iin a GIS Environment (Longley P, Batty M, eds). Cambridge, MA:Geoinformation International, 1996;269–285.
50. Hearne SA. Tracking toxics: chemical use and the public's "Right-to-Know." Environment 38(6):6–33 (1996).
51. National Research Council. National Academy of Sciences. Human Exposure Assessment for Airborne Pollutants, Advances and Opportunities. Washington, DC:National Academy Press, 1991.
52. New York City Department of Environmental Protection. The Greenpoint-Williamsburg Environmental Benefits Program. New York:NYC DEP, 1995.
53. Ahearn SC, Osleeb JP. The Greenpoint/Williamsburg Environmental Benefits Program: Development of a Pilot Geographic Information System. In: Proceedings of the GIS/LIS, 2-4 November 1993. Minneapolis, MN:GIS/LIS 1993;10–18.
54. McMaster RB, Leitner H, Sheppard E. GIS-based environmental equity and risk assessment: methodological problems and prospects. Cartogr Geogr Inform Sys 24(3):172–189 (1997).
55. Pratt GC, Gerbec PE, Livingston SK, Oliaei F, Bollweg GL, Paterson S, Mckay D. An indexing system for comparing toxic air pollutants based on their potential environmental impacts. Chemosphere 27(8):1359–1379 (1993).
56. Neumann CM, Forman DL, Rothlein JE. Hazard screening of chemical releases and environmental equity analysis of populations proximate to toxic release inventory facilities in Oregon. Environ Health Perspect 106(4):217–226 (1998).
57. The methodology for the development of a baseline aggregate environmental load index and a cumulative air pollutant profile is given in the following two documents: Maantay JA, Timander L, Graziosi G, Meyers L. The Bronx Toxic Release Inventory Report. New York:Center for a Sustainable Urban Environment/United States Environmental Protection Agency, 1997; and Maantay JA. Urban Air Pollution, Respiratory Disease, and Environmental Justice: Making the Links in the South Bronx, New York City. Discussion Paper. New York: Center for a Sustainable Urban Environment, 1996. The baseline aggregate environmental load (BAEL) index was developed by the City University of New York/Hunter College Center for Occupational and Environmental Health (Dan Kass), Department of Urban Affairs, Graduate Program in Urban Planning (Hilda Blanco, Bill Milczarski), and Department of Geography (Jeff Osleeb, Sean Ahearn), under contract to the New York City Department of Environmental Protection, for the Greenpoint–Williamsburg Environmental Benefits Program. The BAEL index is based on a model developed in the Netherlands and makes use of the environmental indicators methodology developed by ABT Associates. ABT Associates. Toxic Release Inventory: Environmental Indicators Methodology. Bethesda MD:ABT Associates, 1992. See also Miller D, de Roo G. Integrated environmental zoning: an innovative Dutch approach to measuring and managing environmental spillovers in urban regions. Am Plan Assoc J 62(3):373–380 (1996) and Sol VM, Lammers PM, Aiking H, DeBuer J, Geenstra JF. Integrated environmental index for application in land-use zoning. Environ Manage 19(3):457–467 (1995).
58. Jia CQ, Di Guardo A. Toxic release inventories: opportunities for improved presentation and interpretation. Environ Sci Technol 30:86–91 (1996).
59. Sheppard E, Leitner H, McMaster RB, Hongguo T. GIS-based measures of environmental equity: exploring their sensitivity and significance. J Expos Anal Environ Epidemiol 9:18–28 (1999).
60. National Oceanic and Atmospheric Administration and the U.S. Environmental Protection Agency. User's Manual for Area 1 Locations of Hazardous Atmospheres (ALOHA). Washington, DC:National Safety Council, 1992.
61. Chakraborty J, Armstrong MP. Exploring the use of buffer analysis for the identification of impacted areas in environmental equity assessment. Cartogr Geogr Inform Sys 24(3):145–157 (1997).
62. Ulirsch GV, Gable DL, Lee V. Integration of particulate air modeling with a GIS: an exposure assessment of emissions from two phosphate-processing plants. In: Proceedings of GIS Conference: Third National Conference on Geographic Information Systems in Public Health, 17-20 August 1998, San Diego, CA. Atlanta, GA:Agency for Toxic Substances and Disease Registry. Available: *http://www.atsdr.cdc.gov/GIS/Conference98/proceedings/html/ulirsch.html* [accessed 21 December 2001].
63. Dunn C, Kingham S. Establishing links between air quality and health: searching for the impossible? Social Sci Med 42(6):831–841 (1996).
64. Maslia ML, Aral MM, Williams RC, Susten AS, Heitgerd JL. Exposure assessment of populations, using environmental modeling, demographic analysis, and GIS. Water Resour Bull 30(6):1025–1041 (1994).
65. Aberley D. Boundaries of Home: Mapping for Local Empowerment. Philadelphia:New Society Publishers, 1993.
66. Convis C, ed. Conservation Geography: Case Studies in GIS, Computer Mapping, and Activism. Redlands, CA:ESRI Press, 2001;7.
67. Maantay JA. Zoning, equity, and public health. Am J Public Health 91:1033–1041 (2001).
68. Maantay JA. Industrial Zoning Changes and Environmental Justice in New York City: An Historical, Geographical, and Cultural Analysis [PhD Thesis]. New Brunswick, NJ:Rutgers University, 2000.
69. New York City Department of City Planning. Locating City Facilities: A Guide to the "Fair Share" Criteria. New York: NYC DCP, 1991.
70. Lake R. Rethinking NIMBY. Am Plan Assoc J 59:90 (1993).
71. Heiman M. From "Not in My Back Yard!" to "Not in Anybody's Back Yard!": Grassroots Challenge to Hazardous Waste Facility Siting. Am Plan Assoc J 56:359–362 (1990).
72. Haggerty M. Crisis at Indian Creek. In: Unequal Protection: Environmental Justice and Communities of Color (Bullard RD, ed). San Francisco:Sierra Club Books, 1996;23–42.
73. Wright B, Bryant P, Bullard R. Coping with poisons in Cancer Alley. In: Unequal Protection: Environmental Justice and Communities of Color (Bullard R, ed). San Francisco:Sierra Club Books, 1996;110–129.
74. Robinson R. West Dallas versus the lead smelter. In: Unequal Protection: Environmental Justice and Communities of Color (Bullard R, ed). San Francisco: Sierra Club Books, 1996;92–109.
75. Austin R, Schill M. Black, brown, poor, and poisoned: minority grassroots environmentalism and the quest for eco-justice. Kansas J Law Public Policy 1:69–82 (1991).
76. Bullard RD. Dumping in Dixie: Race, Class, and Environmental Quality. Boulder, CO:Westview Press, 1990.
77. Wernette DR, Nieves LA. Breathing polluted air: minorities are disproportionately exposed. EPA J 18:16–17 (1992).
78. White H. Hazardous waste incineration and minority communities: the case of Alsen, Louisiana. In: Race and the Incidence of Environmental Hazards (Bryant B, Mohai P, eds). Boulder, CO:Westview Press, 1992.
79. Johnston BR, Dawson S. Resource use and abuse on Native American land: uranium mining in the American Southwest. In: Who Pays the Price: The Sociocultural Context of Environmental Crisis (Johnston BR, ed). Washington, DC:Island Press, 1994;142–153.
80. Novotny P. Popular epidemiology and the struggle for community health in the environmental justice movement. In: The Struggle for Ecological Democracy (Faber D, ed). New York:Guilford Press, 1998;137–158.
81. West P, Fly JM, Marans R, Larken F, Rosenblatt D. Minorities and toxic fish consumption: implications for point discharge policy in Michigan. In: Environmental Justice: Issues, Policies and Solutions (Bryant B, ed). Washington, DC:Island Press, 1995;124–137.
82. Agency for Toxic Substances and Disease Registry, Public Health Service. The Nature and Extent of Lead Poisoning in Children in the United States: A Report to Congress. Washington, DC:U.S. Department of Health and Human Services, 1988.
83. U.S. Environmental Protection Agency. Costs and Benefits of Reducing Lead In Gasoline: Final Regulatory Impact Analysis. Washington, DC:Office of Policy, Planning and Evaluation, 1985.
84. Friedman MS, Powell KE, Hutwagner L, Graham LM, Teague WG. Impact of changes in transportation and commuting behaviors during the 1996 Olympic Games in Atlanta on air quality and childhood asthma. J Am Med Assoc 285 (7):897–905 (2001).
85. U.S. Bureau of the Census. Census of Population and Housing, 1990 Summary Tape File on CD-Rom. Technical Documentation. Washington, DC:U.S. Bureau of the Census, 1990.
86. New York City Department of Sanitation. Inventory List of Waste-Related Facilities Permitted by NYC DOS. Obtained through Freedom of Information Law request letter, 11 April 2000.
87. New York State Department of Environmental Conservation. Inventory list of waste-related facilities permitted by NYS DEC. Obtained from NYS DEC through Freedom of Information Law request letter, 11 April 2000.
88. New York City Department of City Planning. Citywide Industry Study: Geographical Atlas of Industrial Areas. New York:NYC DCP, 1993.